

Intracluster Stars and the Galactic Halos of Virgo

John J. Feldmeier¹, Robin Ciardullo^{1,2}, Roger Bartlett

Department of Astronomy and Astrophysics, Penn State University, 525 Davey Lab, University Park, PA 16802

George H. Jacoby

Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726

Abstract.

Planetary nebulae can be useful dynamical probes of elliptical galaxy halos, but progress thus far has been hampered by the small data samples available for study. In order to obtain a large sample of planetary nebulae for dynamical analysis, we have re-observed the giant elliptical galaxy M87 in the center of the Virgo Cluster. Surprisingly, we find that the M87 sample is contaminated by a significant fraction of intracluster objects. Follow up observations of three blank fields in the cluster confirm that a significant fraction of Virgo's starlight is intracluster. We discuss the implications of intracluster stars for studies of galaxy halos in clusters.

1. Planetary Nebulae as probes of galactic halos:

Measuring the dark matter halos of elliptical galaxies is a difficult task. Unlike disk galaxies, there are few dynamical tracers in ellipticals that can be observed over large ranges in distance. Stellar absorption features and emission line gas disks cannot be used much beyond two effective radii (r_e), and although X-ray mass determinations can be invaluable at large radii, currently X-ray observations cannot reach the centers of ellipticals, due to instrumental resolution, and potential complications due to cooling flows.

Planetary nebulae (PN) are objects that are extremely well suited to bridge the gap between inner and outer dynamical methods. Individual PN can be easily detected at several r_e with 4-m class telescopes out to distances of ~ 20 Mpc., and samples already exist for over twenty elliptical galaxies. Since PN emit a large fraction ($\sim 15\%$) of their flux in a single narrow emission line at 5007 \AA , their velocities can be determined with a short duration spectrum at moderate, $\lambda/\Delta\lambda \sim 5000$ resolution. Finally, PN are excellent distance indicators

¹Visiting Astronomer, Kitt Peak National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

²NSF Young Investigator

Figure 1. This is our $16' \times 16'$ [O III] image of M87, created by combining seven one-hour exposures with the Kitt Peak 4-m telescope. North is up, and east is to the left. The 337 PN candidates found in this survey are denoted as squares.

(for a review, see Jacoby 1996a), through the Planetary Nebulae Luminosity Function distance method (PNLF), which allows the true physical scale of the system to be determined.

There have been a handful of detailed dynamical studies of elliptical galaxies out to several r_e , using PN (for a current review, see Arnaboldi & Freeman 1997). However, with the notable exception of NGC 5128 (Hui et al. 1995), these studies suffer from relatively poor statistics; typically, the samples observed to date are less than a hundred objects. Without more data, it is impossible to explore multi-component dynamical models of halos: the only analysis possible is to assume simple models and test for consistency. Clearly, this could lead to erroneous results. For example, if elliptical galaxies are formed via encounters between galaxies, then box or tube orbits along the galaxy's major or minor axis may be the rule, and most of the system's angular momentum (and possibly mass) may reside far in the halo (Barnes 1988, 1992). If this is the case, then the stellar distribution function will be extremely anisotropic and the mass-to-light ratio will change with radius. To investigate these possibilities, several hundred test particle velocities (Merrifield & Kent 1990; Merritt & Saha 1993) are needed.

To rectify this limitation, we re-observed the giant elliptical galaxy M87 with a wide field ($16' \times 16'$) CCD camera on the Kitt Peak 4-m telescope. This survey yielded a total of 337 PN candidates for use in a dynamical study.

2. The Problem: an unusual luminosity function

Figure 2 (left) plots the planetary nebula luminosity function for a statistical sample of M87's PN. From these data, the PNLF distance to the galaxy can normally be derived by convolving the empirical model for the PNLF given by Ciardullo et al. (1989):

$$N(M) \propto e^{0.307M} [1 - e^{3(M^* - M)}] \quad (1)$$

with the photometric error function and fitting the data to the resultant curve via the method of maximum likelihood. However, in the case of M87, the most likely empirical curve (the solid line) is a poor fit to the luminosity function. Kolmogorov-Smirnov and χ^2 tests both exclude the Ciardullo et al. law at the 99.9% confidence interval. This is a remarkable result: none of the PNLFs from any of the ~ 30 previously studied galaxies differs significantly from the empirical law. Moreover, the large number of PN detected in this survey cannot be invoked to explain the discrepancy. The luminosity functions of M31, M81, NGC 5128, and NGC 4494 all contain similar numbers of objects. The planetaries surrounding M87 are therefore unique in some way.

An even more surprising result comes if we divide our PN sample in two, and compare the PNLFs of M87's inner and outer halo (first noted in Jacoby,

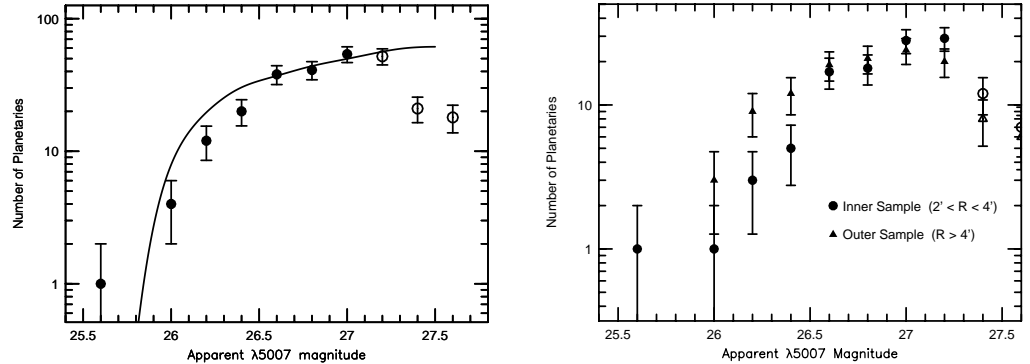


Figure 2. On the left is the planetary nebula luminosity function for a statistical sample of M87 planetaries. The curve shows the empirical function shifted to the most likely distance modulus. Although this curve is the “best fit” to the data, it is still excluded at the 99.9% confidence level. On the right, we have divided the sample of M87’s PN into two samples, as described in the text. As can be clearly seen the outer sample has many more bright objects.

1996a). For the inner sample, we take all the PN in our statistical sample with isophotal radii between $2'$ and $4'$; for the outer sample, we take those PN with $r_{\text{iso}} > 4'$. Both samples are plotted in Figure 2 (right). Of the 20 brightest PN, 18 belong to the outer sample. More importantly, the shapes of the two PNLFs appear different: a Kolmogorov-Smirnov test reveals that the two samples are different at the 92% confidence level. Again, this result is unique. Explicit tests for changes in the PNLF cutoff with galactocentric radius have been performed with the large samples of PN available in NGC 5128 and NGC 4494. In neither case was a gradient observed.

3. The Explanation:

Internal and external tests on the ~ 30 early and late-type galaxies surveyed to date have shown that the location of the PNLF cutoff does not depend on the properties of the parent stellar population (cf. Jacoby 1996b). However, a number of mechanisms do exist which can, at least in theory, cause the PNLF technique to fail and produce a change in the observed value of m^* . The first, and simplest, is to hypothesize that some instrumental effect exists, such as a radial gradient in the flatfield or the transmission curve of the filter. We have run a number of tests, and have ruled out an instrumental effect in our data.

A second possibility is to invoke non-uniform extinction in M87. Dust has been detected in the central regions of many elliptical galaxies (Ebner, Djorgovski, & Davis 1988), and it is possible in principle that dust might cause

the difference between our inner and outer samples. However, studies of dust have concentrated on the central regions of elliptical galaxies, while our survey deals exclusively with PN that are more than $1.5 r_e$ from the galactic nucleus. Moreover, even if there is a strong gradient in the dust distribution, this still may not translate into an observed gradient in m^* . As Feldmeier, Ciardullo, & Jacoby (1997) have shown, the location of a galaxy's PNLF cutoff is relatively insensitive to the presence of dust, as long as the scale length for the obscuration is smaller than that of the stars. This makes it very unlikely that dust is responsible for the change in m^* .

Although the absolute magnitude of the PNLF cutoff is extremely insensitive to the details of the underlying stellar population, a dramatic change in the metallicity or age of M87's halo stars could, in principle, produce a change in m^* similar to that observed. Both observations and theory suggest that galaxies with $[O/H] \lesssim -0.5$ can have a PNLF cutoff that is different from that of metal-rich populations by ~ 0.1 mag. Unfortunately, this effect acts in the wrong direction: it is the metal-poor systems that have fainter values of M^* . In order to explain the observed gradient, the center of M87 would have to be metal-poor, and the halo would need to be metal-rich. Observations show that this is extremely unlikely (Kormendy & Djorgovski 1989).

Similarly, it is difficult to use population age to explain PNLF variations. According to the models of Dopita, Jacoby, & Vassiliadis (1992) and Méndez et al. (1993), the location of the PNLF cutoff is nearly independent of age for populations between 3 and 12 Gyr. If these models are correct, then in order to enhance the luminosity of the PNLF cutoff in M87's outer halo, one must hypothesize an unrealistically young age for the stars, ~ 0.5 Gyr.

The best hope for explaining the observed changes in M87's halo PNLF lies in the Virgo Cluster itself. All of the above explanations implicitly assume that the PN projected onto M87's outer halo are at the same distance as those PN which are members of the inner sample. However, if the Virgo Cluster has a substantial population of intracluster stars, this will not be the case, as some objects will be superposed in the foreground, and others will be in the background. For example, if the Virgo Cluster is at a distance of ~ 15 Mpc, then the central 6° core of the cluster (de Vaucouleurs 1961), has a linear extent of ~ 1.5 Mpc. If the core is spherically symmetric and filled with stars, then we might expect some intracluster objects to be up to ~ 0.25 mag brighter than the value of m^* derived from galaxies at the center of the cluster. This is roughly what is observed in Figure 2.

Further evidence that the anomalous PNLF of M87 is due to foreground contamination comes from the fact that it is the outer sample of objects that has most of the bright PN. The number of foreground PN detected in any region of our CCD field should be roughly proportional to the area of the field; since the outer region samples ~ 8 times more area than the inner field, those data should contain ~ 8 times more intracluster objects. In addition, M87's sharply peaked surface brightness profile guarantees that the ratio of galaxy light to intracluster light in the inner field will be much larger than that in the outer field. Consequently, the contribution of intracluster objects to the inner sample will be small, while that for the outer sample will be relatively large. Again, this is roughly what is displayed in Figure 2.

Although the idea of intracluster planetary nebulae (IPN) seems speculative, there is, in fact, conclusive evidence that such objects do exist. In their radial velocity survey of 19 PN in the halo of the Virgo Cluster elliptical M86 ($v = -220 \text{ km s}^{-1}$), Arnaboldi et al. (1996) found three objects with $v > 1300 \text{ km s}^{-1}$. These planetaries are undoubtedly intracluster in origin. Significantly, the PN observed by Arnaboldi et al. were originally identified with a 30 \AA filter centered at 5007 \AA (Jacoby, Ciardullo, & Ford 1990); intracluster objects with $v > 1000 \text{ km s}^{-1}$ should have been strongly excluded. The only reason three were detected was that at $v \sim 1500 \text{ km s}^{-1}$, $[\text{O III}] \lambda 4959$ is shifted into the bandpass of the $[\text{O III}] \lambda 5007$ filter! Since $I(\lambda 5007)/I(\lambda 4959) = 3$, only the very brightest PN could have been detected in this way. The existence of three intracluster objects in the Arnaboldi et al. sample therefore implies the presence of many more.

4. The Confirmation:

Motivated by our studies of M87, we decided to search the Virgo Cluster to confirm the presence of intracluster PN. We observed three $16' \times 16'$ blank fields: one at the isopleth center of subclump A (subclumps defined by Binggeli, Tammann & Sandage 1987) $52'$ away from M87, one $\sim 36'$ north of the giant elliptical NGC 4472 in subclump B, and a third due north of the M87 field shown above. In the first two fields, we identify 69 and 16 intracluster planetary nebulae candidates, respectively. In the third field near M87, we detect 75 planetary nebulae candidates, of which the majority can be attributed to M87. However, like the M87 data shown above, the empirical PNLF is again a poor fit to the observed luminosity function observed for Field 3: a Kolmogorov-Smirnov test excludes the Ciardullo et al. (1989) law at the 93% confidence level. From our determination of the distance to M87 (Ciardullo et al. 1997), and the expected PNLF for M87 PN, we can show that at least ten planetaries, and probably more, are intracluster in origin. The combined data from the three fields confirms the intracluster hypothesis for M87.

5. PN as probes of intracluster starlight: some preliminary results

Intracluster PN are interesting objects in their own right, not simply contaminants to galactic halo samples. Ever since Zwicky (1951) first claimed the detection of excess light between galaxies of the Coma Cluster, intracluster light has been of great interest to astronomers. Depending on the efficiency of tidal stripping, this intracluster component will contain anywhere between 10% and 70% of the cluster's total luminosity (Richstone & Malumuth 1983; Miller 1983). It is therefore a sensitive probe of how tidal-stripping works, the distribution of dark matter around galaxies, and of the initial conditions of cluster formation.

We can use our PN observations to trace the amount of stellar light distributed in the Virgo intracluster medium. Renzini & Buzzoni (1986) have shown that the bolometric-luminosity specific stellar evolutionary flux of non-star-forming stellar populations, should be $\sim 2 \times 10^{-11} \text{ stars-yr}^{-1} L_{\odot}^{-1}$, independent of population age or initial mass function. If the lifetime of the planetary nebula stage is $\sim 25,000 \text{ yr}$, then every stellar population should have

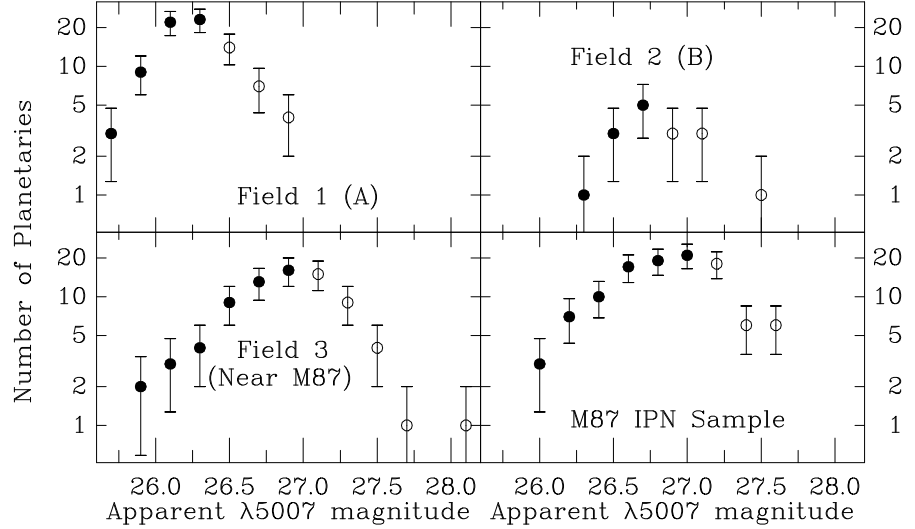


Figure 3. The planetary nebula luminosity functions for the three intracluster fields, plus a sample of suspected intracluster planetaries from M87, binned into 0.2 mag intervals. The solid circles represent objects in our statistical IPN samples; the open circles indicate objects fainter than the completeness limit. Note that the numbers of intracluster planetaries vary from field to field.

$\alpha \sim 50 \times 10^{-8} \text{ PN} \cdot L_{\odot}^{-1}$. Observations in ellipticals have shown that no galaxy has a value of α greater than this number, though α can be a factor of five smaller (Ciardullo 1995). Nevertheless, the direct relation between the number of planetary nebulae and the parent system’s luminosity allows us to estimate the number of stars in Virgo’s intergalactic environment. When we apply this calculation to our data, taking the α value that produces the minimum amount of starlight necessary to reproduce the data, we find an estimated $6 \times 10^9 L_{\odot}$ in the two $16' \times 16'$ intracluster fields. We note that this is the minimum amount of starlight necessary to explain the data, and the amount could be greater by up to a factor of five. If we compare this to the amount of starlight in galaxies, we find that the intracluster stars produce at least 26% of the total stellar luminosity of Virgo.

Another interesting result is the dramatically different numbers of intracluster PN in Fields 1 and 2. Although the survey depths of the regions differ (due to differences in sky transparency and seeing), it is clear that the highest density of intracluster objects is in Field 1, at the center of subclump A. After accounting for the differing depths, the density of PN in Field 2, which is near the edge of the 6° Virgo Cluster core in subclump B, is down by a factor of ~ 4 . The fact that subclump B has fewer PN than subclump A can probably be attributed to cluster environment. It is well known that subclump B has fewer early-type galaxies than subclump A (Binggeli, Tammann, & Sandage 1987). If ellipticals and intracluster stars have a related formation mechanism (i.e., galaxy

interactions), then a direct correlation between galaxy type and stellar density in the intergalactic environment might be expected.

Clearly, further data is needed to confirm and support these results. However, it is clear that there is a significant amount of intracluster starlight in the Virgo Cluster that must be taken into account when dynamical studies are undertaken. If intracluster objects are ignored, then the derived M/L ratio will be overestimated, due to the much larger velocity dispersion associated with the cluster.

6. Future plans and prospects:

The analysis of the dynamics of Virgo's stars has already begun. We have obtained data on M87's PN velocities from the WIYN telescope, and will soon begin observing intracluster PN with the Hobby-Eberly Telescope (HET). Although our sample of M87 objects is contaminated with intracluster objects, it may be possible to separate out the populations using the PNLF and by modeling the velocity distribution of intracluster objects.

In order to learn much more about intracluster PN, we are continuing our [O III] $\lambda 5007$ Virgo survey. Intracluster PN provide information on both the two dimensional and, by using the PNLF, three dimensional structure of the cluster. Through the velocities and spatial distribution of intracluster PN, we can determine whether models of "galaxy harassment" (Moore et al. 1996) can explain the large amounts of intracluster starlight. In the future, intracluster stars should be a useful tool in understanding galaxy clusters, and the nature of galactic halos.

Acknowledgments. We would like to thank the organizing committee for giving us the opportunity to present this work orally. This work was supported in part by NASA grant NAGW-3159

References

- Arnaboldi, M. & Freeman, K. C. 1997, in *The Second Stromlo Symposium: The Nature of Elliptical Galaxies*, ed. M. Arnaboldi, G.S. Da Costa & P. Saha (Astronomy Society of the Pacific, San Francisco), p. 54
- Arnaboldi, M., Freeman, K.C., Mendez, R.H., Capaccioli, M., Ciardullo, R., Ford, H., Gerhard, O., Hui, X., Jacoby, G.H., Kudritzki, R.P., & Quinn, P.J. 1996, *ApJ*, 472, 145
- Barnes, J.E. 1988, *ApJ*, 331, 699
- Barnes, J.E. 1992, *ApJ*, 393, 484
- Binggeli, B., Tammann, G. A., & Sandage, A. 1987, *AJ*, 94, 251
- Ciardullo, R. 1995, in *IAU Highlights of Astronomy*, 10, ed. I. Appenzeller (Dordrecht: Kluwer), p. 507
- Ciardullo, R., Jacoby, G. H., Feldmeier J. J., & Bartlett, R. 1997, *ApJ*, in press
- Ciardullo, R., Jacoby, G.H., Ford, H.C., & Neill, J.D. 1989, *ApJ*, 339, 53
- de Vaucouleurs, G. 1961, *ApJS*, 6, 213

- Dopita, M.A., Jacoby, G.H., & Vassiliadis, E. 1992, *ApJ*, 389, 27
- Ebner, K., Djorgovski, S., & Davis, M. 1988, *AJ*, 95, 422
- Feldmeier, J.J., Ciardullo, R., & Jacoby, G.H. 1997, *ApJ*, 479, 231
- Hui, X., Ford, H.C., Freeman, K.C. & Dopita M.A. 1995, *ApJ*, 449, 592
- Jacoby, G.H. 1996a, in *The Extragalactic Distance Scale*, ed. by M. Livio, M. Donahue, & N. Panagia (Cambridge University Press), in press
- Jacoby, G.H. 1996b, in *IAU Symposium 180, Planetary Nebulae*, ed. by H. Habing & H. Lamers (Kluwer, Dordrecht), in press
- Jacoby, G.H., Ciardullo, R., & Ford, H.C. 1990, *ApJ*, 356, 332
- Kormendy, J., & Djorgovski, S. 1989, *ARA&A*, 27, 235
- Méndez, R.H., Kudritzki, R.P., Ciardullo, R., & Jacoby, G.H. 1993, *A&A*, 275, 534
- Merrifield, M.R., & Kent, S.M. 1990, *AJ*, 99, 1548.
- Merritt, D., & Saha, P. 1993, *ApJ*, 409, 75.
- Miller, G.E. 1983, *ApJ*, 268, 495
- Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A. 1996, *Nature*, 379, 613
- Renzini, A., & Buzzoni, A. 1986, in *Spectral Evolution of Galaxies*, ed. C. Chiosi, & A. Renzini (Dordrecht: Reidel), p. 195
- Richstone, D.O., & Malumuth, E.M. 1983, *ApJ*, 268, 30
- Zwicky, F. 1951, *PASP*, 63, 61

This figure "fig1.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9711208v1>